7th Int. Symp. "Nanostructures: Physics and Technology" QW/SL.03
St Petersburg, Russia, June 14–18, 1999

Impact of Fano resonances on the Wannier–Stark ladder

C. P. Holfeld†, T. W. Canzler†, D. M. Whittaker‡, F. Löser†, M. Sudžius†, K. Leo† and K. Köhler§

† Institut für Angewandte Photophysik, Technische Universität Dresden, 01062 Dresden, Germany
‡ Toshiba Research Europe Ltd., 260 Cambridge Science Park, Milton Road, CB4 0WE Cambridge, United Kingdom
§ Fraunhofer–Institut für Angewandte Festkörperphysik, 79108 Freiburg, Germany

Abstract. We report on the observation of Fano resonances in electrically biased superlattices. In such structures, Coulomb interaction couples discrete exciton states to continua of lower-lying subbands. We thus observe Fano resonances on the Wannier–Stark states. In superlattices, it is possible to continuously tune the coupling strength by sweeping the electric field. We prove this by linear absorption spectroscopy which demonstrates that the coupling and the line asymmetry change with field. We also measured the polarization decay of the Wannier–Stark transitions and found a decrease of the dephasing times for growing Fano coupling strength.

Introduction

Degeneracy of discrete states and a continuum is often found in nature. The quantum mechanical coupling of such degenerate discrete and continuous states gives rise to Fano resonances which lead to major changes of the optical spectra by quantum interference of the transition paths. Fano interference manifests itself by a strong, asymmetric deviation from the natural line shape together with a broadening due to the coupling. The quantum mechanical coupling is also expressed by a reduction to zero transition probability on one side of the resonance below the former continuum level.

Fano resonances appear in various systems since they are not restricted to a certain origin of the states or their interaction. They are indeed an universal phenomenon in physics. The theory has originally been developed by Fano to understand rare gas spectra [1]. In semiconductor physics, electron–electron and phonon–electron interaction are subject to Fano resonances. In particular, the Fano effect is generally predicted in low-dimensional semiconductors [2] since confinement usually forms excitonic subbands which are coupled by the Coulomb interaction. This has experimentally been confirmed in quantum wells [3], bulk GaAs in a magnetic field [4] and electrically biased superlattices [5]. As a new attempt, the Fano coupling strength can be manipulated by either changing the density of continuum states [6] or varying the coupling matrix element [5].

1 Fano coupling and superlattices

A Fano system needs only a few, generalized prerequisites. Consider a discrete state $|d\rangle$ which is energetically degenerate with a continuum of states $|c\rangle$ (see Fig. 1). These states are Fano coupled by an interaction Hamiltonian $\hat{V}$. Finally, the Fano system is experimentally probed by a transition from a common ground state $|g\rangle$ (transition operator $\hat{T}$). It should be noted that there is no restriction on the actual origin of both the states and the participating

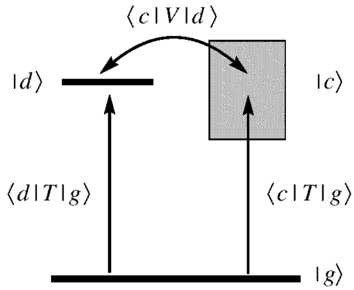

Fig. 1. Schematic overview about the energy states involved in Fano coupling.

interactions. Due to the Fano coupling $\hat{V}$, the transition paths to discrete and continuous states are no longer independent but do quantum mechanically interfere in respect to their phase-locking.

The mathematical analysis of Fano assumes a delta-like discrete state coupled to a quasi-continuous set of discrete states with an uniform density of states in the zero-spacing limit [1]. Coupling between different continuum states is neglected. The probing transition then results no longer in a sharp line. Its profile is modified by asymmetric broadening and is given by the line shape formula g:

$$g(\varepsilon) = \frac{(q+\varepsilon)^2}{1+\varepsilon^2} \qquad \varepsilon = \frac{E - E_R}{\frac{1}{2}\Gamma} \tag{1}$$

$$\Gamma = 2\pi\,|\langle c|\hat{V}|d\rangle|^2 \tag{2}$$

The argument ε is a normalized energy difference in respect to a resonance energy E_R in units of the spectral broadening Γ. This parameter Γ is solely dependent on the Fano coupling probability and is not influenced by the transition process. The line shape formula (1) contains also a parameter q which strongly determines the asymmetry and depends on the excitation conditions.

The Fano effect is generally predicted in low-dimensional semiconductors [2]. Here confinement splits the electronic bands into several subbands. Due to Coulomb interaction there are several bound (discrete) excitons just below every subband edge followed by an ionization continuum of unbound excitons. Thus, the discrete excitonic states are degenerate with the ionization continua of lower-lying subbands. Coupling of them is again mediated by the Coulomb interaction.

This situation is also found in superlattices. An axial electric field splits the quasi-3D miniband into an equidistantly spaced ladder of subbands, the so-called Wannier–Stark ladder (WSL). The splitting $\Delta E = eFd$ of the subbands is directly dependent on the applied electric field F (d—superlattice period). The ladder transitions are labeled with $\mathrm{hh}_{\pm n}$ according to heavy hole transitions to the nth neighbour well on the energetically raised (+) or dropped (−) side.

The discrete excitonic states are Fano-coupled to the continua of lower-lying ladder states as described in the previous paragraph. In comparison to other systems, superlattices offer the unique possibility of continuously tuning the Fano coupling by simply sweeping the applied electric field. This varies the splitting of the WSL which corresponds to a changing momentum mismatch of discrete state and continuum. We thus expect weaker Fano coupling with increasing field.

2 Results and discussion

Our measurements are carried out on GaAs/$Al_{0.3}Ga_{0.7}As$ superlattices with a barrier/well width of 17 Å or 67 Å, respectively. The temperature of the sample has been kept at approximately 10 K during mesurements. First, the field-dependent evolution of Fano resonances has been observed using a standard setup for absorption spectroscopy with correction of the halogen lamp spectrum. When applying an electric field in growth direction of the superlattice, the absorption of the miniband and of its related heavy and light hole excitons disappears. Instead the Wannier–Stark states develop as described in the previous section. An example of the obtained spectra is shown in Fig. 2. It turns out that the transitions to all ladder states exhibit a rather large line width and distinct asymmetry with the slow rise on the low-energy side. This observation is made over the whole field range where there is a pronounced oscillator strength of the transitions. The line width is found to decrease with growing field in accordance with increasing ladder spacing. Coupling of the Wannier–Stark excitons to lower subband continua is thus impeded resulting in a narrower profile.

The absorption has also been calculated theoretically for comparison. The numerics is based on the direct solution of the Schrödinger equation considering the confinement potential of biased superlattices and the presence of Coulomb interaction between electrons and holes [7]. The only free parameters are the absolute scaling of absorption and some phenomenological broadening due to interface roughness and field inhomogeneities. The calculations thus naturally include Fano resonances. A comparison of experimental and theoretical absorption spectra reveals strong correspondence. Almost all spectral details are reproduced by theory. A fit of the Fano line shape formula to the calculated spectra in the absence of extra broadening is used to obtain values of the Fano coupling parameter Γ (Eq. (1), (2)). There is a pronounced decrease of Γ with growing field supporting the experimental observation.

We have also investigated the polarization decay by means of transient four-wave mixing (FWM). These measurements are restricted to the hh_{-1} transition because it has a strong oscillator strength and a distinct dependence of the energetic position on the applied field. The spectral pulse width is set to about 7 meV (corresponding to 300 fs) thus ensuring

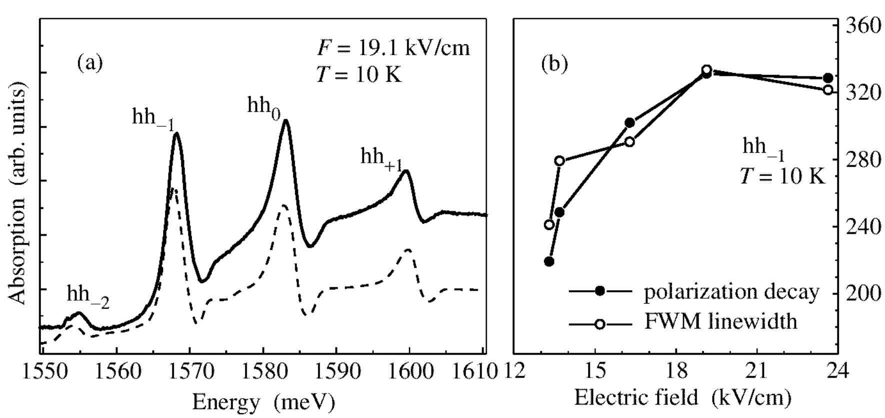

Fig. 2. (a) Example of experimental (solid line) and theoretical (dashed line) absorption spectrum of a 67/17 Å superlattice. (b) Dephasing times for the hh_{-1} transition at varying electric fields due to the decay time and linewidth of the FWM signal.

the excitation of only one Wannier–Stark transition even at a small ladder splitting. The centre of the laser is shifted approximately 2 meV below the absorption peak to prevent an incoherent carrier background. We obtain a clearly resolved decay of the FWM signal in contrast to a previous study on bulk GaAs in a magnetic field [8]. Both the rise and decay time of the signal is well above the autocorrelation limit. The polarization decay time systematically rises for stronger fields which is not expected for collisional broadening. We thus attribut the slower polarization decay to the weaker discrete state-continuum coupling $|\langle c|\hat{V}|d\rangle|^2$ resulting in a reduced Fano line width Γ.

Acknowledgements

We gratefully thank D. S. Chemla and S. Glutsch for their helpful discussions, T. Hasche and V. G. Lyssenko for experimental help. This work was financially supported by the Deutsche Forschungsgemeinschaft.

References

[1] U. Fano, *Phys.Rev.* **124**, 1866 (1961).
[2] S. Glutsch, D. S. Chemla and F. Bechstedt, *Phys. Rev. B* **51**, 16885 (1995).
[3] D. Y. Oberli *et al.*, *Phys. Rev. B* **49**, 5757 (1994).
[4] S. Glutsch *et al.*, *Phys. Rev. B* **50**, 17009 (1994).
[5] C. P. Holfeld *et al.*, *Phys. Rev. Lett.* **81**, 874 (1998).
[6] J. Faist *et al.*, *Optics Letters* **21**, 985 (1996).
[7] D. M. Whittaker, *Europhys. Lett.* **31**, 55 (1995).
[8] U. Siegner *et al.*, *Phys. Rev. Lett.* **74**, 470 (1995).